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Rhesus Monkey Aversion to 94-GHZ Facial Exposure

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14. ABSTRACT
Millimeter wave (MMW) source technology has advanced significantly allowing the use of 94-GHz MMWs as a non-lethal weapon. The Air Force Research Laboratory has developed such a non-lethal weapon known as the Active Denial System (ADS). The purpose of this study was to determine the threshold for behavioral aversion to 94-GHz MMW exposure in rhesus monkeys. Aversion was defined simply as an eye blink, head turn, or raising the hand to block the 94-GHz MMW beam. Six rhesus monkeys were occasionally exposed to a 94-GHz beam that was turned on for brief periods to deliver energy densities (fluence) that ranged from 0.2 J/cm^2 to 2.2 J/cm^2. An infrared camera produced a series of thermographs during the exposure so that facial skin and eye temperature could be correlated with behavioral aversion. The energy density thresholds that produced these behavioral responses on 50% of the exposures and the maximum facial (and ocular) temperature changes were determined to be in the range of 0.4 J/cm^2 to 1.0 J/cm^2 and produce maximum temperature changes of 1 °C to 3.2 °C on the face or cornea of the eye. Eye blink was most sensitive to the MMW exposures. Head turn or hand raising required higher energy densities than that required to produce eye blinks. Aversion to 94-GHz MMWs begins at 0.4 J/cm^2 and is a robust response at 1.0 J/cm^2. These effects occur well below the temperature rise in the skin needed to produce pain (10 °C). These data along with human exposure data will be used to specify safe exposure levels for the ADS system.

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Naval Health Research Center Detachment
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Technical Report – NHRC DEBL TR-2006-07

RHESUS MONKEY AVERSION THRESHOLDS TO 94-GHz FACIAL EXPOSURE

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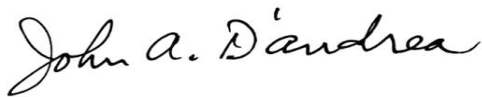
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This research was in compliance with the Animal Welfare Act and adhered to the principles enunciated in the Guide for the Care and Use of Laboratory Animals per SECNAVINST 3800.38B.

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TABLE OF CONTENTS

Executive Summary

Background

Millimeter wave (MMW) source technology has advanced significantly allowing the use of 94 GHz MMWs as a non-lethal weapon. The Air Force Research Laboratory has developed such a non-lethal weapon known as the Active Denial System (ADS). It uses high-power MMWs to thwart an individual or group of individuals from advancing or entering restricted areas. Within seconds of the exposure, a targeted individual feels an uncomfortable skin heating sensation that stops when the transmitter is shut off or when the individual moves out of the MMW beam. The natural behavior of a person experiencing such a sensation is to quickly escape the beam. The primary effect of the ADS is heating of the skin and eye by absorption of the 94 GHz millimeter waves. Developing dose-response relationships between MMW exposure and the resulting thermal effect on the skin and eye and the behavioral response will be important for effective use of the ADS system.

Objectives

The purpose of this study was to determine the threshold for behavioral aversion to 94 GHz MMW exposure in rhesus monkeys. Aversion was defined simply as an eye blink, head turn, or raising the hand to block the 94 GHz MMW beam. This study would provide valuable information prior to a similar study with human subjects.

Approach

Six rhesus monkeys were trained to perform an observing task for food reward that was unrelated to delivery of the 94 GHz MMW beam. Occasionally, during performance of this task, the 94 GHz beam was turned on for brief periods to deliver energy densities (fluence) that ranged from 0.2 J/cm^2 to 2.2 J/cm^2. The monkey's performance on the behavioral observing task and aversion responses to the 94 GHz beam were recorded. An infrared camera produced a series of thermographs during the exposure so that skin and eye temperature could be correlated with the behavioral and aversion responses.

Results

The aversion responses videotaped during each exposure were scored by five independent observers for the three behaviors: eye blink, head turn, or raising the hand. The energy density thresholds that produced these behavioral responses and the maximum facial (and ocular) temperature changes were determined to be in the range of 0.4 J/cm^2 to 1.0 J/cm^2. Exposures in this range of energy densities produce maximum temperature changes of 1 °C to 3.2 °C on the face or cornea. Eye blink during exposure was associated with the lowest energy density of MMW exposure while turning of the head and raising a hand occurred at slightly higher energy densities.

Conclusions

The purpose of the study reported here was to correlate behavioral responses with fluence of 94 GHz MMW irradiation and produce a dose-response function for aversion to 94 GHz MMWs. Aversion to 94 GHz MMWs begins at 0.4 J/cm^2 and is a robust response at 1.0 J/cm^2. These

2

effects occur well below the temperature rise in the skin needed to produce pain (10 °C). These data, along with human exposure data, will be used to specify safe but effective exposure levels for the ADS system.

Abstract

Millimeter wave (MMW) source technology has advanced significantly allowing the use of 94 GHz MMWs as a non-lethal weapon. The Air Force Research Laboratory has developed such a non-lethal weapon known as the Active Denial System (ADS). The purpose of this study was to determine the threshold for behavioral aversion to 94 GHz MMW exposure in rhesus monkeys. Aversion was defined simply as an eye blink, head turn, or raising the hand to block the 94 GHz MMW beam. Six rhesus monkeys were occasionally exposed to a 94 GHz beam that was turned on for brief periods to deliver energy densities (fluence) that ranged from 0.2 J/cm^2 to 2.2 J/cm^2. An infrared camera produced a series of thermographs during the exposure so that facial skin and eye temperature could be correlated with behavioral aversion. The energy density thresholds that produced these behavioral responses on 50% of the exposures and the maximum facial (and ocular) temperature changes were determined to be in the range of 0.4 J/cm^2 to 1.0 J/cm^2 and produce maximum temperature changes of 1 °C to 3.2 °C on the face or cornea of the eye. Eye blink was the first behavioral response to the MMW exposures and occurred at the lowest energy density. Head turn or hand raising required higher energy densities than that required to produce eye blinks. Aversion to 94 GHz MMWs begins at 0.4 J/cm^2 and is a robust response at 1.0 J/cm^2. These effects occur well below the temperature rise in the skin needed to produce pain (10 °C). These data along with human exposure data will be used to specify safe exposure levels for the ADS system.

Introduction

Absorption of electromagnetic energy in the microwave and millimeter wave range is determined by the induced electric fields in the tissues and the electrical properties of the tissues. High water content tissue, such as skin, absorbs energy in this frequency range very well. The electrical properties and frequency of the beam also determine the depth of penetration. Millimeter wave fields, at 94 GHz, are absorbed in the first few tenths of a millimeter, while lower frequencies with longer wavelengths penetrate much more deeply (Gandhi and Riaz, 1986). Recent calculations from Alekseev et al., (2008) have used two sets of permittivity parameters to calculate depth of skin penetration by MMWs. As shown in Figure 1 the depth of penetration varies inversely with frequency. The penetration depth for the heterogeneous skin was calculated as the distance into the skin where intensity decreased to e^{-2} of its original value. Thus, absorption of 94 GHz MMW in the skin causes heating in the first 0.4 mm of tissue (Alekseev et al., 2008). The depth of penetration into the cornea is estimated to be in the range of 0.16 mm (Foster et al., 2003) to 0.33 mm (Gandhi and Riaz, 1986). This is significant for the ADS because many of the free nerve endings, which are thought to signal thermal sensation and discomfort, are located in approximately the first 0.2 mm of the skin and cornea. A diagram of the cornea of the eye, showing likely depth of penetration, is given in Figure 2.
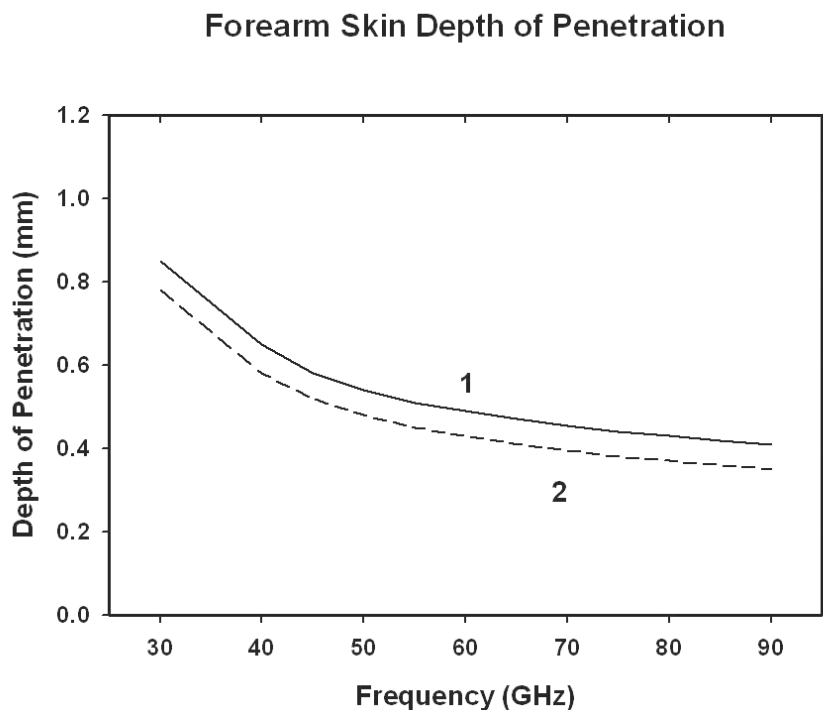

Figure 1 Penetration depth of the plane MMW field in human forearm skin. Calculations were performed using permittivity values for the forearm skin given by the authors (curve 1) and by Gandhi and Riazi [1986] (curve 2). (Redrawn from Alekseev et al., 2008).
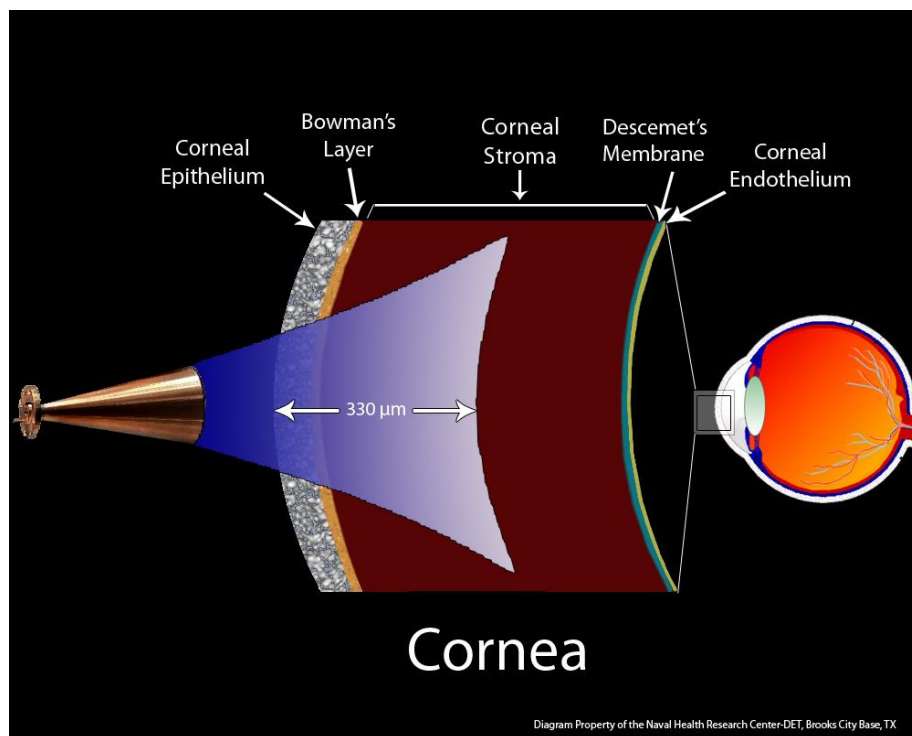
Figure 2.   A diagram of the cornea of the eye with depth of penetration of 94 GHz radiation shown.

Operational use of the ADS will result in frontal MMW exposures that will include exposure of the face and eyes. The primary effect of the ADS on the skin and eye is heating by absorption of the 94 GHz millimeter waves.   Heating will continue, during exposure, until the beam is terminated or the subject moves out of the beam. Thus short term exposures, even at high power densities, can produce safe rates of heating to achieve the desired effect. However, longer durations can produce injurious levels of skin or eye heating. The damage thresholds have been reported in the biomedical literature for thermal stimulation of the skin. For example, Moritz and Henriques (1947) in their classic study published in 1947 determined the temperature-duration relationships, of 1st and 2rd degree burns with pigs and human subjects, by contact with hot water. They established, for example, the threshold for a 1st degree burn in human subjects as requiring 57ºC for 5 sec, and 57ºC for 10 sec to produce 2nd degree burns. Also, previous research has documented the threshold for minor thermal damage to the epithelium of the cornea in anesthetized monkeys who could not avoid the 94 GHz exposure (Chalfin et al., 2002). The time and temperature thresholds for minor epithelial damage at 94 GHz were roughly 55º to 60º C (corneal surface temperature) for 2 to 4 sec exposures.

The skin and eye studies described above documented the temperature-duration relationship for thermal damage to skin and cornea. Other studies have documented the thresholds for both detection and thermal pain. A study by Blick et al. (1997) measured detection thresholds on the skin in the middle of the back of human subjects. They used long duration (10-s), large area (327-cm2) stimuli to minimize temporal or spatial summation. Frequencies of 2.45, 7.5, 10, 35, and 94 GHz as well as infrared (IR) were tested. The detection thresholds decreased more than an order of magnitude from 2.45 GHz to 94 GHz. The 94 GHz threshold (4.5 mW/cm2) was comparable to the IR detection threshold (5.34 mW/cm2) threshold.   A recent report in the

5

biomedical literature by Walters et al., (2000) described irradiation of a spot on the back of 10 human subjects with 94 GHz radiation and time to reports of pain. They determined the pain threshold for exposure to 1.25 W/cm^2, to be 3 sec at a skin temperature of 43.9 °C ± 0.5°C.
It is important to also document the level of exposure that elicits protective responses. Therefore evaluations of aversion responses to facial exposures are important prior to ADS being fielded as a non-lethal weapon. One of the goals of the biological effects research program, sponsored by the Joint Non-lethal Weapons Directorate, has been to separate the deterrent effects of the ADS from harmful thermal effects. This is a dose-response question that may best be answered by evaluating the effects of 94 GHz energy absorption at both low power densities and high power densities. The biological effects of MMW require detailed study from thresholds of sensory detection, to aversion and, up to levels that cause thermal injury. High-level MMW exposures at 94 GHz need to be studied because little scientific research has been done at MMW frequencies at high power levels. This experiment is one in a series designed to document the effects of 94 GHz exposures from low, barely detectable intensities, to high power induced thermal damage. .

In the study reported here, we test the response of alert awake monkeys to 94 GHz exposure where the natural response is aversion to the 94 GHz MMW beam. Thus aversion, in this behavioral study, was simply defined as an eye blink, head turn, or raising a hand to block the 94 GHz MMW beam. Eye blinking during and following a thermal stimulus is a reflex that occurs in humans and is probably the same for all individuals unless disease or some other factor has modified reflexes in some way. The monkeys were given a food motivated behavioral task which required attention to be directed at a visual stimulus (see D'Andrea et al., 1994). Food was given when the visual stimulus changed. Thus, the behavioral task resulted in monkeys observing the visual stimulus most of the time allowing a full facial exposure to the 94 GHz beam radiating from an antenna located next to the visual stimulus.

Methods and Materials

Subjects   The subjects for this experiment were six Rhesus monkeys (*Macaca mulatta*), weighing between 8.1 and 9.6 kg and ranging in age from 9 to 10 years old. The monkeys were housed on Brooks City-Base in a standard vivarium environment, caged individually, with automatic lights set to a 12-hour light/dark cycle and provided with environmental enrichment programs. Ambient temperature in the vivarium was maintained between 19-22 °C. An automated monitoring system notified personnel if temperature ranges deviated from specifications. The animals involved in this study were procured, maintained, and used in accordance with the Federal Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals," prepared by the Institute of Laboratory Animal Resources -- National Research Council. Formal approval to conduct these experiments was received from the Air Force Research Laboratory Animal Care and Use Committee at Brooks City-Base, TX under Navy Protocol 02-10.

The rhesus monkey (*Macaca mulatta*) was used in this study because this species has proven to be a good surrogate for humans in many sensory experiments. For example, Rozsa et al. (1985) measured the thermal sensitivity of humans and monkeys using a signal detection paradigm. They concluded that responses between the two species were very similar and that the neural systems responsible for coding thermal information are fundamentally the same between the two species. Other studies have compared the visual systems of rhesus monkeys and humans and

concluded that the rhesus monkey has nearly the same visual capabilities and is a good model for the human visual system (Harwerth, et al., 1985).

Apparatus

Primate Chair The monkeys were trained to sit in a chair while they performed the visually guided behavioral task. The chair was made of PVC plastic (Special Designs, Inc.) and was designed to allow the subjects as much freedom of movement as possible. The subjects were fitted with PVC collars (Special Designs, Inc.) which had loops made of nylon rope covered in plastic tubing. The loops were fastened on hooks to keep the subject in place in the primate chair. The subjects could move their arms and legs and rotate their bodies 360 degrees on the vertical axis, yet were fixed in place, both horizontally and vertically. The loops also allowed handlers to attach poles in order to direct the animal's movement to and from the transport cage and primate chair.

Response Panel The behavioral response panel on the primate chair was also made of PVC (Special Designs, Inc.), and consisted of two levers separated by a reinforced food delivery cup. For this task, the monkey pulled the right lever and responded when signaled by a visual stimulus using the left lever. Responses were monitored by the use of fiber optic switches that detected beam breaks caused by response lever presses. The panel was mounted to the primate chair in such a way as to enable the monkey to reach the levers and see the food cup.

Millimeter Wave Exposure System The exposure facility consisted of a 6.1m X 9.15m anechoic chamber.   Inside the anechoic chamber a smaller 3.7m X 3.7m Styrofoam® environmentally controlled room provided consistent temperature and humidity control. Exposures to energy densities ranging from 0 to 2.2 J/cm^2 were performed using a MMW exposure system in a far field exposure facility based on a coupled cavity traveling wave tube amplifier with an output of 800 W (North Star Research Corporation). The exposure setup consisted of 94 GHz standard gain horn with a built-in waveguide window to allow waveguide pressurization with SF6 gas. The output of the horn was aligned to deliver the 94 GHz beam to the area occupied by the monkey's face. The monkey was positioned so that the face was 2.25m from the front surface of the standard gain horn. Measurements of field power density were done at 2.25m. The center of the beam was located with a FLIR infrared camera and a carbon-impregnated target. Once the center of beam was located, the infrared camera monitor was marked to show the location of the center of the beam and the carbon material would be removed. A MMW detector was positioned at this location and the output of the transmitter was measured. This procedure was completed daily before each experimental run and the detector was calibrated weekly to a known source. The detector equipment consisted of: HP-437B Power Meter (with power reference for automatic calibration and zeroing), HP-8486A Waveguide Power Sensor, M&M FA-10-10 75GHz-110GHz Power Attenuator 10Watt, Millitech FXA-10-R2OPO 10dB Fixed Attenuator, Millitech Standard Gain Horn.

Measurement Technique Once the center of the beam was located and a measurement taken with the HP-437B power meter and horn assembly, the indicated power would be input into a correction formula. Example: The power meter reads XXXmW at the center of beam with the transmitter repetition rate set at 100Hz. The attenuation inline was 10.35 and the effective area of the horn was 1.68 cm^2, XXXmW * 10.35 / 1.68 = XXXmW per 100 pulses. XXXmW / 100 = XXX mW/cm^2 per pulse. After the power density was measured, the transmitter's maximum

allowed pulse rate was calculated and entered into the experimental control software. This limited the maximum output to no more than the maximum power permitted by the protocol. Power output of the MMW oscillator was controlled by manipulating the duty cycle (ratio of pulse-on time to pulse-off time) of a 1 kHz rectangular wave pulse train that gated the output of the oscillators. Pulse durations (50–500 µs) to produce the required duty cycles (5–50%) were calculated by a computer (Micron, 233 MHz, Micron Technology, Inc., 8000 S. Federal Way, PO Box 6, Boise, ID 83707-0006) and sent to a programmable function generator (HP 8116A) that produced pulse trains with the required time duration to produce the desired energy density at the monkey's face.

Transmitter Control Program A LABVIEW computer program controlled the transmitter output power by manipulating the pulse duration and repetition rate. The operator could input desired power density and the duration. The program calculated and adjusted the pulse repetition rate to achieve the desired power density and set the trigger to provide the required duration. The program also calculated and displayed the total output energy density (J/cm^2). The role of the 94 GHz transmitter operator was to monitor the subject visually and the status of the exposure process. Pre-trial exposure setup consisted of the operator setting the desired power density and pulse duration and closing and holding a normally open interlock switch allowing a trigger signal to be sent to the transmitter producing the proper exposure. If at any time the operator detected a problem, the switch could be released and the transmitter exposure terminated. Holding the interlock switch, the operator would then trigger the control program to deliver the prescribed exposures.

Facial Temperature Measurements A FLIR System ThermaCAM SC 3000 (FLIR Systems, Boston, MA) IR system was used to record facial temperature during exposures. The camera was mounted on a tripod at the same distance from the subject as the MMW high-gain horn. At a distance of 2.25m, a 10 degree telephoto lens was used to obtain more detail of the subject's exposed face. ThermaCAM Researcher 2.7 IR software was used to control the camera and acquire image data at a rate of 60 frames per second. A start signal for infrared image collection was generated by the computer that controlled the MMW source. The software described above was used to measure temperature of the IR images. An external calibration for the camera was performed using a black-body source (Mikron, Model M340, Mikron Instrument Company, Inc., 16 Thornton Road, Oakland, NJ 07436).

Procedures

Feeding Schedule Water was freely available in each animal's home cage. Weekday feeding consisted of food pellets earned during tasks plus 4-12 biscuits (Lab Diet 5045 High Protein Monkey Diet) - depending on the monkey's weight and how well the monkey performed the behavioral task. More food was given if the monkey performed the task well and worked continuously throughout the session. Fruit and treats were given to each animal on working days. Fruit consisted of an entire apple, orange, or banana. Weekend and holiday feeding consisted of 18-20 biscuits, 2 times a day on Saturday and 5 biscuits in AM Sunday with no food in PM. Following this schedule provided adequate motivation for the monkeys to perform the behavioral task to earn food reward. Holiday feeding was the same as Saturday, with the day before a return to work set equal to the Sunday schedule.

Animals were food restricted during working days and most of their daily ration working on the operant task during the experiment. In addition, on each working day, animals received at least one type of food treat in conjunction with their environmental enrichment devices. Types of treats given were; various flavors of Prim Treats (Bio-Serv), Marshmallows, Peanut Butter, crumble disks (Bio-Serv), Nutrablocks (Bio-Serv), and raisins.

Monkey Handling Transport cages were used in order to move animals from their home cage to the behavioral testing area. The transport cage was placed against the door of the home cage and both doors opened, allowing the animal to move freely from the home cage. The transport cage was then covered with a canvas hood, and the weight of the animal was obtained, and placed on a cart and rolled a short distance (120 ft) to the testing area. Technicians used the two-man pole and collar technique to move the animals from the transport cage to the behavioral chair (Anderson and Houghton, 1983). Upon completion of testing, the procedure was reversed and the animals were returned to their home cages.

Behavioral Training The monkeys were trained on a multiple schedule using visual signals as discriminative stimuli. The monkeys were first habituated to the chair for several sessions and then trained by successive approximation to pull the left lever for food pellet reward. The schedule was divided into two main parts. In the first part, a red light was associated with responses on the right lever during a variable interval (VI) schedule (5-22 s range). In the second part, green and white lights were associated with responses on the left lever (choice reaction time component). A response on the left lever during the green signal resulted in a food pellet, whereas a response on the left lever during the white signal resulted in a 30 s timeout period and no food pellet. The green light was initially set to stay on for 30 seconds or until the subject pressed the left lever and received a banana pellet. Over the days of training the duration of the green light was incrementally lowered until it would stay on for only 2 seconds. This is essentially a Go/NoGo (also called Recognition) reaction time task in which subjects respond to one particular event but ignore other events.

Final Behavioral Task All animals were run for 30 minutes. The session was computer driven and the task required the monkey to press the right lever a minimum of 5 times to a maximum of 22 times. This was done while they looked at a red light. When the light changed to green, they were to then press the left lever within 2 seconds. If the left lever was not pressed in the allotted time, an incorrect tone sounded, signaling a 2 second time-out. If the monkey performed the task accurately, a correct tone sounded and a reinforcer consisting of a banana pellet (Bioserv) was delivered. If the monkey pressed the left lever during a red light, an incorrect tone sounded and no reinforcer was delivered. If a white light was presented, the monkey could continue pressing the right lever without consequence. Pressing the left lever in response to a white light resulted in an incorrect tone and a 2 second time-out penalty.
Baseline sessions were run the same as in training, with no outside noise other than an exhaust fan. Sham sessions were conducted with transmitter in standby with the MMW beam off. Trials (Exposures) were run with transmitter and MMW beam on. Prior to beginning of all sessions, all metal was removed from the test chamber.

Millimeter Wave Exposures The subjects were individually tested in the plastic restraint chair with neck brace that allowed accurate positioning of the face relative to the MMW beam. The monkeys were exposed to brief bursts of MMW energy that produced energy densities of 0.2 J/cm^2 to 2.2 J/cm^2 at the monkey's face as well as Sham exposures with the MMW beam blocked

from reaching the subject. These energy densities are well below the levels known to produce pain in the human (Walters et al., 2000) but greater than the know threshold of detection (Blick et al., 1997). Subject alignment was provided by using the IR camera focus and the area of interest (AOI) set in the camera viewfinder. Operators performed daily system checks and dosimetry prior to the start of exposure sessions. The test equipment used during the calibrations and dosimetry received regular maintenance and calibration by an offsite local, Air Force sponsored calibration facility (Preventive Maintenance Equipment Laboratory, Brooks City-Base, TX). Onsite, daily equipment checks insured the power heads and other equipment used remained in excellent working order. The initial process of the daily dosimetry was described above. This limited the maximum output to no more than the maximum power permitted by the protocol.

Behavioral Aversion Data Scoring All sham and MMW exposures were recorded by a DVD video recorder (Panasonic Model PV D-4762). The video data was scored (the several frames immediately after exposure) by six independent observers who evaluated each sham exposure and MMW exposure and scored the monkeys response according to a scoring system developed at this laboratory. The scoring system was created by breaking behaviors into 3 groups; HEAD, HAND, and EYE BLINK. Each group was then broken down into discrete behaviors and numbered (example- No Blink – 0, Blink – 1, Multiple Blinks – 2, Closed Eyes - 3). The scoring system was initially tested by having two observers score all video files and note any problems or vagueness. The final Video Scoring Instruction Sheet and observer scoring packets were then developed. Once all monkey exposure and sham exposure trials were scored, these data were entered into Sigmaplot © (SPSS Inc. Chicago IL) analysis and graphing program. Data was entered into a spreadsheet as each observer completed scoring a monkey's behavior. These data were imported into NCSS© statistical program (NCSS, Kaysville Utah) and a Repeated Measures ANOVA was performed to determine if scoring between observers were either consistent or significantly different (inter-rater reliability analysis). The data files were separated into HEAD, HAND and EYE BLINK Sigmaplot© graph files.

Statistical Analysis To investigate the relationship between the independent (energy density) and dependent (behavioral response and facial temperature) variables, each data set was graphed using the Sigmaplot © (SPSS Inc. Chicago IL). Using this application, the data were subjected to linear regression analyses, and correlation coefficients (R) and analysis of variance (ANOVA). Power for each test, reported by the software, was 1.00 ($P<0.05$) unless otherwise noted. This was the probability that a statistical significance test will reject the null hypothesis for a specified value of the alternative hypothesis. The HEAD, HAND and EYE BLINK data were further categorized in binary fashion (0= no response or 1=response) for each level of MMW exposure. Logistic regression was done using SYSTAT, version 11 (SPSS 1999, SPSS, Inc., 233 S. Wacker Drive, Chicago, IL 60606), which also provided the cumulative predicted probabilities of the dependent variable for each data set.

<center>**Results**</center>

Facial Temperature Analyses Temperature calibrated images taken with the infrared camera for each MMW exposure were scanned and a mean temperature for the image was computed. Minimum and maximum temperatures in each image were also recorded. The maximum facial (and ocular) temperature changes are shown in Figure 3. The ANOVA showed that as the

energy density was increased the maximum facial temperature change significantly increased ($F_{(1,299)} = 1058$, P< 0.0001) with a linear positive correlation (R=0.88).
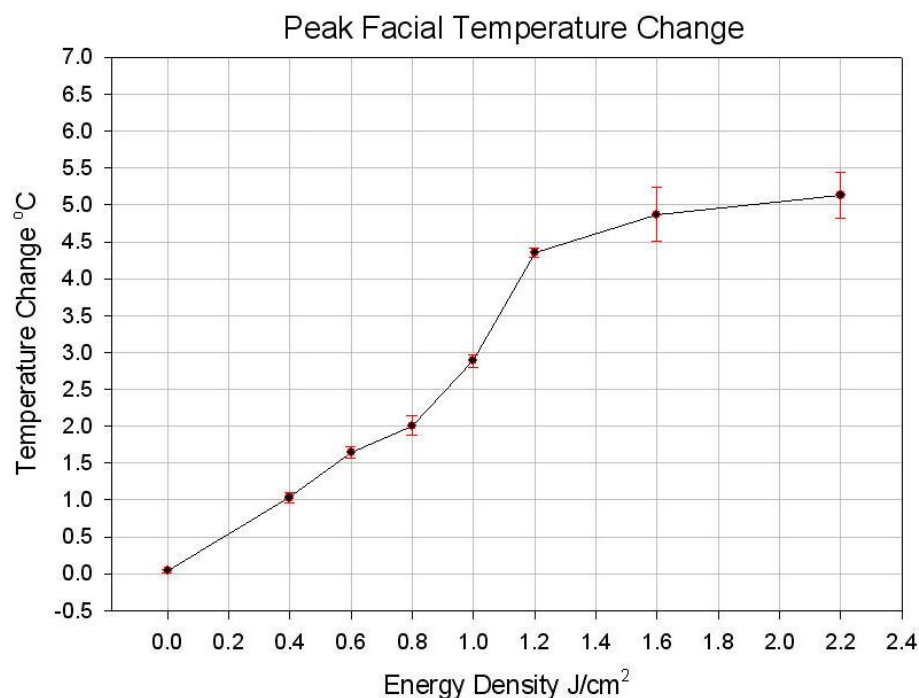

Figure 3. Peak facial temperatures of monkeys exposed to Sham (0 J/cm^2) and MMW 0.6 to 2.2 J/cm^{-2}.

Logistic Regression Analyses Five of the six independent observers successfully scored the aversion data, each exposure and sham trial, and noted whether a blink, head turn, or raising the hand gesture occurred. The sixth observer had significant difficulty seeing the video images of the monkey face and was removed from the data set. This binary data, yes or no that a response occurred, was first subjected to a repeated measures one-way analysis of variance (RMANOVA) to determine the agreement of the five observers in scoring the data. This analysis found no significant difference between the five independent observers ($F_{(4,2422)}$= 1.24, P=0.29) indicating they all scored the video data in a similar way.

The data was then subjected to a logistic regression analysis to determine the probability of an event (blink, head turn, hand raise) occurring based on the energy density of each sham or exposure. Logistic regression allows one to predict a discrete outcome, such as eye blink, from a set of variables, in this case energy density of the sham or MMW exposure. That is how likely a behavior, such as blink, will occur, given the accompanying independent variable of energy density. The results of this analysis are plotted in Figure 4 showing that eye blink was most sensitive to the MMW exposures while turning of the head and raising a hand occur at slightly higher energy densities (see Figure 4). These values for the 50% threshold are given in Table 1 along with the associated peak temperature change.
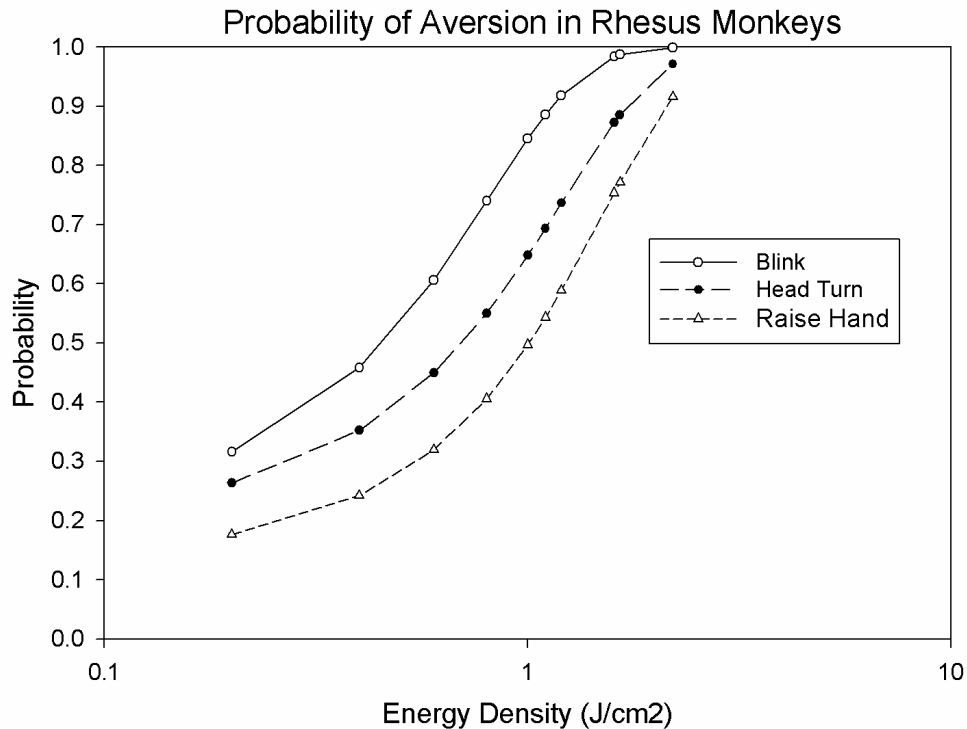
Figure 4. Probability of a behavioral response during exposures of monkeys to 94 GHz.

Behavior	Energy Density	Temperature Change
Eye blink	0.4 J/cm^2	~ 1.0 °C
Head turn	0.8 J/cm^2	~ 2.0 °C
Hand raise	1.0 J/cm^2	~ 3.2 °C

Table 1. Threshold energy density necessary to elicit eye blinking, head turning, and hand raising during 94 GHz exposure. Maximum facial temperature change is shown for each exposure.

Behavioral Performance Monkeys performed the observing task quite well with few errors and short latencies to respond to the green light. Inter-response times (IRTs) are defined as the time interval between lever responses and represent how well the monkey maintained a steady response rate. IRTs were collected during baseline pre-exposure and MMW exposure sessions. When these are presented as a ratio, a value of 1 would indicate that the two sessions overall were not different and the monkey performed well. If the IRT value was less than 1 then the monkey responded more quickly on the response lever during the exposure session than it did on the pre-exposure session. On the other hand, as was the case in this study the monkeys always responded more slowly during MMW exposure sessions than they did during pre-exposure and the IRT values were always greater than 1. The IRT values are presented in Figure 5 for each of the energy densities tested, showing that IRTs and energy density were significant but quite variable. As the energy density was increased the IRT ratio increased significantly ($F_{(1,289)} = 14.2$, $P < 0.0002$) but this was a weak association with a linear positive correlation (R=0.22).
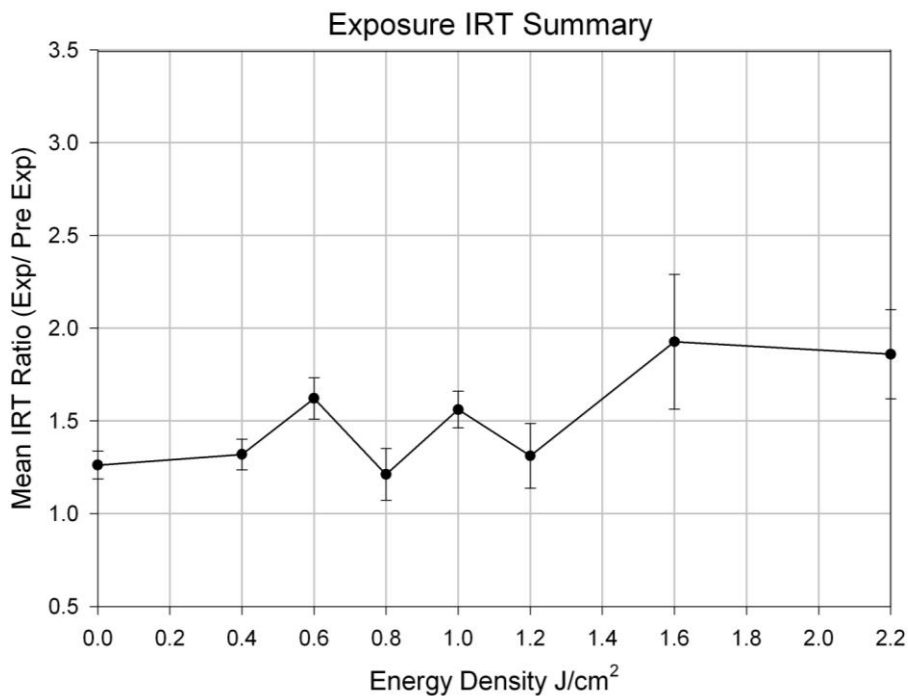
Figure 5. Mean inter-response times (IRT) of monkeys exposed to Sham (0 J/cm^2) and MMW 0.6 to 2.2 J/cm^{-2}.

Discussion

Beuerman and Tanelian (1979), using a water bath technique, reported that humans describe a corneal temperature change of 3 °C to 6 °C as irritating, whereas temperature change to produce pain was 10.1 °C. Walters et al. (2000) reported that pricking pain on the skin of the back in humans exposed to 94 GHz required a 9.9 °C temperature change. Since the rhesus monkey is often used as a model for humans in temperature sensitivity experiments, it is safe to assume that the monkeys in the experiments described above did not experience pain since the largest temperature increase recorded on the eye or face was 5.5 °C. Thus, aversion to 94 GHz exposures by the monkeys seems to occur at energy densities that can be described as irritating but well below the painful level.

In summary, the detection of and aversion to 94 GHz MMWs by monkeys occur at relatively low levels of exposure. The detection threshold is around 4 mJ/cm^2 and the aversion begins near 0.4 J/cm^2. Aversion occurs robustly (>90% of the time) at 1.2 J/cm^2 during exposures. The temperature levels that could be measured on the face of the monkey during the aversion tests were typically less than 3.2°C above pre-exposure temperatures and never greater than 5.5 °C. These did not achieve the well known pain threshold for cornea or skin of 43-45°C (10.1 °C temperature increase). Nevertheless, non-painful exposures were irritating to the monkey and elicited hand raising and head turning in response to the onset of the beam. Exposures below the level that might cause eye aversion (blink) would not damage skin or eyes. Damage is dependent upon tissue temperature and the duration of heating. The blink reflex is a protective mechanism likely elicited by thermally annoying levels of MMW absorption. No damage mechanism other than excessive heating has been identified for MMW exposures.

The reason for conducting this study was to provide additional data from which the margin of safety between effectiveness and injury by ADS could be better defined. Previous research has determined the facial detection threshold, in the nonhuman primate, was 3 mJ/cm^2 (D'Andrea et al. 1999). The research conducted by Chalfin et al. (2002) defined the threshold for a minimal lesion (faint epithelial edema and fluorescein staining) at 5 J/cm^2. The lesions reported by Chalfin et al. (2002) are distinct, involve only the superficial epithelial layers of the cornea, and are reversible within 24-48 hours. In this study we have observed a 0.4 to 1.0 J/cm^2 threshold of injury using behavioral observation techniques. These levels of energy density are the threshold for aversion. The results presented in this report show that aversion follows a dose-response function, with higher energy densities producing greater aversion. As shown above, the variables of aversion (blink, head turn, and hand raising) and energy density were strongly correlated. It is important to note that the aversion responses reported in this study act as protective reflexes and would prevent corneal or facial damage from occurring.

Conclusion

This research study is one part of an overall plan which covered issues of safety margins for skin and eye thermal injuries. The results of this study, taken with the previous eye research, show that 94 GHz exposures produce responses which are time and temperature dependent. Effects on the eye are highly dependent on energy density and because the effective stimulus is joule heating, exposure duration is very important. The pain sensation produced by the ADS system is closely tied to cornea and skin temperature. This study showed that the difference between the thresholds of aversion and mild reversible damage of the cornea (Chalfin et al., 2002) are very large, 0.4 J/cm^2 to 5 J/cm^2. This is a very good margin of safety under which to operate the new ADS technology as a non-lethal weapon.

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